

SOME BEST POSSIBLE INEQUALITIES CONCERNING CERTAIN BIVARIATE MEANS

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Abstract. In this paper, some inequalities of bounds for the Neuman-Sándor mean in terms of weighted arithmetic means of two bivariate means are established. Bounds involving weighted arithmetic means are sharp.

1 Introduction

For $a, b > 0$ with $a \neq b$ the Neuman-Sándor mean $M(a, b)$ [1] is defined by

$$M(a, b) = \frac{a - b}{2 \sinh^{-1} [(a - b)/(a + b)]},$$

where $\sinh^{-1}(x) = \log(x + \sqrt{1 + x^2})$ is the inverse hyperbolic sine function.

Recently, the Neuman-Sándor mean has been the subject of intensive research. In particular, many remarkable inequalities for the Neuman-Sándor mean $M(a, b)$ can be found in the literature [1-4].

Let $H(a, b) = 2ab/(a + b)$, $G(a, b) = \sqrt{ab}$, $L(a, b) = (b - a)/(\log b - \log a)$, $P(a, b) = (a - b)/(4 \arctan \sqrt{a/b} - \pi)$, $A(a, b) = (a + b)/2$, $T(a, b) = (a - b)/[2 \arcsin((a - b)/(a + b))]$, $Q(a, b) = \sqrt{(a^2 + b^2)/2}$ and $C(a, b) = (a^2 + b^2)/(a + b)$ be the harmonic, geometric, logarithmic, first Seiffert, arithmetic, second Seiffert, quadratic and contra-harmonic means of a and b , respectively. Then it is well-known that the inequalities

$$\begin{aligned} H(a, b) &< G(a, b) < L(a, b) < P(a, b) < A(a, b) \\ &< M(a, b) < T(a, b) < Q(a, b) < C(a, b) \end{aligned}$$

hold for all $a, b > 0$ with $a \neq b$.

In [1, 2], Neuman and Sándor proved that the double inequalities

$$A(a, b) < M(a, b) < T(a, b),$$

$$P(a, b)M(a, b) < A^2(a, b),$$

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$$A(a, b)T(a, b) < M^2(a, b) < (A^2(a, b) + T^2(a, b))/2$$

hold for all $a, b > 0$ with $a \neq b$.

Let $0 < a, b < 1/2$ with $a \neq b$, $a' = 1 - a$ and $b' = 1 - b$. Then the following Ky Fan inequalities

$$\frac{G(a, b)}{G(a', b')} < \frac{L(a, b)}{L(a', b')} < \frac{P(a, b)}{P(a', b')} < \frac{A(a, b)}{A(a', b')} < \frac{M(a, b)}{M(a', b')} < \frac{T(a, b)}{T(a', b')}$$

were presented in [1].

The double inequality $L_{p_0}(a, b) < M(a, b) < L_2(a, b)$ for all $a, b > 0$ with $a \neq b$ was established by Li et al. in [3], where $L_p(a, b) = [(b^{p+1} - a^{p+1})/((p+1)(b-a))]^{1/p}$ ($p \neq -1, 0$), $L_0(a, b) = 1/e(b^b/a^a)^{1/(b-a)}$ and $L_{-1}(a, b) = (b-a)/(\log b - \log a)$ is the p -th generalized logarithmic mean of a and b , and $p_0 = 1.843 \dots$ is the unique solution of the equation $(p+1)^{1/p} = 2 \log(1 + \sqrt{2})$.

Neuman [4] proved that the double inequalities

$$\alpha Q(a, b) + (1 - \alpha)A(a, b) < M(a, b) < \beta Q(a, b) + (1 - \beta)A(a, b)$$

and

$$\lambda Q(a, b) + (1 - \lambda)A(a, b) < M(a, b) < \mu Q(a, b) + (1 - \mu)A(a, b)$$

hold for all $a, b > 0$ with $a \neq b$ if and only if $\alpha \leq (1 - \log(\sqrt{2} + 1))/[(\sqrt{2} - 1) \log(\sqrt{2} + 1)] = 0.3249 \dots$, $\beta \geq 1/3$, $\lambda \leq (1 - \log(\sqrt{2} + 1))/\log(\sqrt{2} + 1) = 0.1345 \dots$ and $\mu \geq 1/6$.

The main purpose of this paper is to find the least values $\alpha_1, \alpha_2, \alpha_3$, and the greatest values $\beta_1, \beta_2, \beta_3$, such that the double inequalities

$$\begin{aligned} \alpha_1 H(a, b) + (1 - \alpha_1)Q(a, b) &< M(a, b) < \beta_1 H(a, b) + (1 - \beta_1)Q(a, b), \\ \alpha_2 G(a, b) + (1 - \alpha_2)Q(a, b) &< M(a, b) < \beta_2 G(a, b) + (1 - \beta_2)Q(a, b), \\ \alpha_3 H(a, b) + (1 - \alpha_3)C(a, b) &< M(a, b) < \beta_3 H(a, b) + (1 - \beta_3)C(a, b) \end{aligned}$$

hold true for all $a, b > 0$ with $a \neq b$.

Our main results are presented in Theorems 1.1-1.3.

THEOREM 1.1. *The double inequality*

$$\alpha_1 H(a, b) + (1 - \alpha_1)Q(a, b) < M(a, b) < \beta_1 H(a, b) + (1 - \beta_1)Q(a, b) \quad (1.1)$$

holds for all $a, b > 0$ with $a \neq b$ if and only if $\alpha_1 \geq 2/9 = 0.2222 \dots$ and $\beta_1 \leq 1 - 1/[\sqrt{2} \log(1 + \sqrt{2})] = 0.1977 \dots$.

THEOREM 1.2. *The double inequality*

$$\alpha_2 G(a, b) + (1 - \alpha_2)Q(a, b) < M(a, b) < \beta_2 G(a, b) + (1 - \beta_2)Q(a, b) \quad (1.2)$$

holds for all $a, b > 0$ with $a \neq b$ if and only if $\alpha_2 \geq 1/3 = 0.3333 \dots$ and $\beta_2 \leq 1 - 1/[\sqrt{2} \log(1 + \sqrt{2})] = 0.1977 \dots$.

THEOREM 1.3. *The double inequality*

$$\alpha_3 H(a, b) + (1 - \alpha_3)C(a, b) < M(a, b) < \beta_3 H(a, b) + (1 - \beta_3)C(a, b) \quad (1.3)$$

holds for all $a, b > 0$ with $a \neq b$ if and only if $\alpha_3 \geq 1 - 1/[2 \log(1 + \sqrt{2})] = 0.4327 \dots$ and $\beta_3 \leq 5/12 = 0.4166 \dots$.

2 Lemmas

In order to prove our main results we need two Lemmas, which we present in this section.

LEMMA 2.1. (See [5, Lemma 1.1]). Suppose that the power series $f(x) = \sum_{n=0}^{\infty} a_n x^n$ and $g(x) = \sum_{n=0}^{\infty} b_n x^n$ have the radius of convergence $r > 0$ and $b_n > 0$ for all $n \in \{0, 1, 2, \dots\}$. Let $h(x) = f(x)/g(x)$, then the following statements are true:

- (1) If the sequence $\{a_n/b_n\}_{n=0}^{\infty}$ is (strictly) increasing (decreasing), then $h(x)$ is also (strictly) increasing (decreasing) on $(0, r)$;
- (2) If the sequence $\{a_n/b_n\}$ is (strictly) increasing (decreasing) for $0 < n \leq n_0$ and (strictly) decreasing (increasing) for $n > n_0$, then there exists $x_0 \in (0, r)$ such that $h(x)$ is (strictly) increasing (decreasing) on $(0, x_0)$ and (strictly) decreasing (increasing) on (x_0, r) .

LEMMA 2.2. Let $p \in (0, 1)$, $\lambda_0 = 1 - 1/[\sqrt{2} \log(1 + \sqrt{2})] = 0.1977 \dots$ and

$$f_p(x) = \sinh^{-1}(x) - \frac{x}{\sqrt{1+x^2} - p(\sqrt{1+x^2} - \sqrt{1-x^2})}. \quad (2.1)$$

Then $f_{1/3}(x) < 0$ and $f_{\lambda_0}(x) > 0$ for all $x \in (0, 1)$.

Proof. From (2.1) one has

$$f_p(0) = 0, \quad (2.2)$$

$$f_p(1) = \log(1 + \sqrt{2}) - \frac{1}{\sqrt{2}(1-p)}, \quad (2.3)$$

$$f'_p(x) = \frac{g_p(x)}{\sqrt{1-x^4}(\sqrt{1+x^2} + p(\sqrt{1-x^2} - \sqrt{1+x^2}))^2}, \quad (2.4)$$

where

$$g_p(x) = \sqrt{1-x^2} \left(\sqrt{1+x^2} + p(\sqrt{1-x^2} - \sqrt{1+x^2}) \right)^2 - \sqrt{1-x^2} - p(\sqrt{1+x^2} - \sqrt{1-x^2}). \quad (2.5)$$

We divide the proof into two cases.

Case 1 $p = 1/3$. Then (2.5) leads to

$$g_{1/3}(0) = 0, \quad g_{1/3}(1) = -\frac{\sqrt{2}}{3} < 0, \quad (2.6)$$

$$g'_{1/3}(x) = \frac{x^3}{\sqrt{1-x^4}} h_{1/3}(x), \quad (2.7)$$

where

$$h_{1/3}(x) = \frac{14}{9(\sqrt{1+x^2} + \sqrt{1-x^2})} - (\sqrt{1+x^2} + \sqrt{1-x^2}) - \frac{\sqrt{1-x^2}}{3}. \quad (2.8)$$

We clearly see that the function $\sqrt{1+x^2} + \sqrt{1-x^2}$ is strictly decreasing in $(0, 1)$. Then from (2.8) we get

$$h_{1/3}(x) < h_{1/3}(1) = -\frac{2\sqrt{2}}{9} < 0 \quad (2.9)$$

for $x \in (0, 1)$.

Therefore, $f_{1/3}(x) < 0$ for all $x \in (0, 1)$ follows easily from (2.2), (2.4), (2.6), (2.7) and (2.9).

Case 2 $p = \lambda_0$. Then (2.3) and (2.5) yield

$$f_{\lambda_0}(1) = g_{\lambda_0}(0) = 0, \quad g_{\lambda_0}(1) = -\sqrt{2}\lambda_0 < 0 \quad (2.10)$$

and

$$g'_{\lambda_0}(x) = \frac{x}{\sqrt{1-x^4}} h_{\lambda_0}(x), \quad (2.11)$$

where

$$\begin{aligned} h_{\lambda_0}(x) = & [(2 - 3\lambda_0 - 2\lambda_0^2) - (3 - 6\lambda_0)x^2]\sqrt{1+x^2} \\ & - [(3\lambda_0 - 2\lambda_0^2) + (6\lambda_0 - 6\lambda_0^2)x^2]\sqrt{1-x^2}. \end{aligned} \quad (2.12)$$

We divide the discussion of this case into two subcases.

Subcase A $x \in (0.9, 1)$. Then from (2.12) and the fact that

$$\begin{aligned} & (2 - 3\lambda_0 - 2\lambda_0^2) - (3 - 6\lambda_0)x^2 \\ & < (2 - 3\lambda_0 - 2\lambda_0^2) - (3 - 6\lambda_0) \times (0.9)^2 = -0.1404 \dots < 0 \end{aligned}$$

we know that

$$h_{\lambda_0}(x) < 0 \quad (2.13)$$

for $x \in (0.9, 1)$.

Subcase B $x \in (0, 0.9]$. Then from (2.12) one has

$$h_{\lambda_0}(0) = 0.8137 \dots > 0, \quad h_{\lambda_0}(0.9) = -0.7494 \dots < 0 \quad (2.14)$$

and

$$h'_{\lambda_0}(x) = \frac{x}{\sqrt{1-x^4}} \mu(x), \quad (2.15)$$

where

$$\begin{aligned} \mu(x) = & [(18\lambda_0 - 18\lambda_0^2)x^2 - (9\lambda_0 - 10\lambda_0^2)]\sqrt{1+x^2} \\ & - [(9 - 18\lambda_0)x^2 + (4 - 9\lambda_0 + 2\lambda_0^2)]\sqrt{1-x^2}. \end{aligned} \quad (2.16)$$

We conclude that

$$\mu(t) < 0 \quad (2.17)$$

for all $x \in (0, 0.9]$. Indeed, if $x \in (0, 1/2)$, then (2.17) follows from (2.16) and the inequality

$$(18\lambda_0 - 18\lambda_0^2)x^2 - (9\lambda_0 - 10\lambda_0^2) < 5.5\lambda_0^2 - 4.5\lambda_0 = -0.6747 \dots < 0.$$

If $x \in [1/2, 0.9]$, then (2.17) follows from (2.16) and the inequalities

$$\begin{aligned}
(18\lambda_0 - 18\lambda_0^2)x^2 - (9\lambda_0 - 10\lambda_0^2) &\leq (18\lambda_0 - 18\lambda_0^2) \times (0.9)^2 - (9\lambda_0 - 10\lambda_0^2) \\
&= 5.58\lambda_0 - 4.58\lambda_0^2 = 0.9242 \dots, \\
(9 - 18\lambda_0)x^2 + (4 - 9\lambda_0 + 2\lambda_0^2) &\geq \frac{1}{4}(9 - 18\lambda_0) + (4 - 9\lambda_0 + 2\lambda_0^2) \\
&= 6.25 - 13.5\lambda_0 + 2\lambda_0^2 = 3.6589 \dots, \\
[(18\lambda_0 - 18\lambda_0^2)x^2 - (9\lambda_0 - 10\lambda_0^2)]\sqrt{1+x^2} \\
&\quad - [(9 - 18\lambda_0)x^2 + (4 - 9\lambda_0 + 2\lambda_0^2)]\sqrt{1-x^2} \\
&\leq (5.58\lambda_0 - 4.58\lambda_0^2)\sqrt{1+(0.9)^2} - (6.25 - 13.5\lambda_0 + 2\lambda_0^2)\sqrt{1-(0.9)^2} \\
&= -0.3514 \dots < 0.
\end{aligned}$$

From (2.14) and (2.15) together with (2.17) we clearly see that there exists $x_0 \in (0, 0.9)$ such that $h_{\lambda_0}(x) > 0$ for $x \in [0, x_0]$ and $h_{\lambda_0}(x) < 0$ for $(x_0, 0.9]$.

Subcases A and B lead to the conclusion that $h_{\lambda_0}(x) > 0$ for $x \in [0, x_0]$ and $h_{\lambda_0}(x) < 0$ for $x \in (x_0, 1)$. Thus from (2.11) we know that $g_{\lambda_0}(x)$ is strictly increasing in $(0, x_0]$ and strictly decreasing in $[x_0, 1)$.

It follows from (2.4) and (2.10) together with the piecewise monotonicity of $g_{\lambda_0}(x)$ that there exists $x_1 \in (0, 1)$ such that $f_{\lambda_0}(x)$ is strictly increasing in $[0, x_1]$ and strictly decreasing in $[x_1, 1)$.

Therefore, $f_{\lambda_0}(x) > 0$ for $x \in (0, 1)$ follows from (2.2) and (2.10) together with the piecewise monotonicity of $f_{\lambda_0}(x)$.

□

3 Proof of Theorem 1.1-1.3

Proof of Theorem 1.1. Since $H(a, b)$, $M(a, b)$ and $Q(a, b)$ are symmetric and homogeneous of degree 1. Without loss of generality, we assume that $a > b$. Let $x = (a - b)/(a + b)$ and $t = \sinh^{-1}(x)$. Then $x \in (0, 1)$, $t \in (0, \log(1 + \sqrt{2}))$, $M(a, b)/A(a, b) = x/\sinh^{-1}(x) = \sinh(t)/t$, $H(a, b)/A(a, b) = 1 - x^2 = 1 - \sinh^2(t) = [3 - \cosh(2t)]/2$, $Q(a, b)/A(a, b) = \sqrt{1+x^2} = \cosh(t)$ and

$$\begin{aligned}
\frac{Q(a, b) - M(a, b)}{Q(a, b) - H(a, b)} &= \frac{\sqrt{1+x^2} \sinh^{-1}(x) - x}{[\sqrt{1+x^2} - (1-x^2)] \sinh^{-1}(x)} \\
&= \frac{t \cosh(t) - \sinh(t)}{t[\frac{1}{2} \cosh(2t) + \cosh(t) - \frac{3}{2}]} := \varphi(t).
\end{aligned} \tag{3.1}$$

Making use of power series $\sinh(t) = \sum_{n=0}^{\infty} t^{2n+1}/(2n+1)!$ and $\cosh(t) = \sum_{n=0}^{\infty} t^{2n}/(2n)!$ we can express (3.1) as follows

$$\varphi(t) = \frac{\sum_{n=1}^{\infty} [2n/((2n+1)(2n)!)] t^{2n+1}}{\sum_{n=1}^{\infty} [(2^{2n-1} + 1)/(2n)!] t^{2n+1}}. \tag{3.2}$$

Let $a_n = 2n/((2n+1)(2n)!)$ and $b_n = (2^{2n-1} + 1)/(2n)!$. Then $a_n/b_n = 2n/(2n+1)(2^{2n-1} + 1)$. Moreover, by a simple calculation, we see that

$$\frac{a_{n+1}}{b_{n+1}} - \frac{a_n}{b_n} = \frac{2 + (2 - 18n - 12n^2)2^{2n-1}}{(2n+1)(2n+3)(2^{2n-1} + 1)(2^{2n+1} + 1)} < 0 \quad (3.3)$$

for $n \geq 1$.

Equations (3.1) and (3.2) together with inequality (3.3) and Lemma 2.1 lead to the conclusion that $\varphi(t)$ is strictly decreasing in $(0, \log(1 + \sqrt{2}))$. This in turn implies that

$$\lim_{t \rightarrow 0^+} \varphi(t) = \frac{2}{9}, \quad \lim_{t \rightarrow \log(1+\sqrt{2})} \varphi(t) = 1 - \frac{1}{\sqrt{2} \log(1 + \sqrt{2})}. \quad (3.4)$$

Therefore, Theorem 1.1 follows from (3.1) and (3.4) together with the monotonicity of $\varphi(t)$. \square

Proof of Theorem 1.2. Since $G(a, b)$, $M(a, b)$ and $Q(a, b)$ are symmetric and homogeneous of degree 1. Without loss of generality, we assume that $a > b$. Let $x = (a - b)/(a + b)$, $p \in (0, 1)$ and $\lambda_0 = 1 - 1/[\sqrt{2} \log(1 + \sqrt{2})]$. Then making use of $G(a, b)/A(a, b) = \sqrt{1 - x^2}$ gives

$$\frac{Q(a, b) - M(a, b)}{Q(a, b) - G(a, b)} = \frac{\sqrt{1 + x^2} \sinh^{-1}(x) - x}{(\sqrt{1 + x^2} - \sqrt{1 - x^2}) \sinh^{-1}(x)}. \quad (3.5)$$

Moreover, we obtain

$$\lim_{x \rightarrow 0^+} \frac{\sqrt{1 + x^2} \sinh^{-1}(x) - x}{(\sqrt{1 + x^2} - \sqrt{1 - x^2}) \sinh^{-1}(x)} = \frac{1}{3}, \quad (3.6)$$

$$\lim_{x \rightarrow 1^-} \frac{\sqrt{1 + x^2} \sinh^{-1}(x) - x}{(\sqrt{1 + x^2} - \sqrt{1 - x^2}) \sinh^{-1}(x)} = 1 - \frac{1}{\sqrt{2} \log(1 + \sqrt{2})} = \lambda_0. \quad (3.7)$$

We take the difference between the additive convex combination of $G(a, b)$, $Q(a, b)$ and $M(a, b)$ as follows

$$\begin{aligned} & pG(a, b) + (1 - p)Q(a, b) - M(a, b) \\ &= A(a, b) \left[p\sqrt{1 - x^2} + (1 - p)\sqrt{1 + x^2} - \frac{x}{\sinh^{-1}(x)} \right] \\ &= \frac{A(a, b)[p\sqrt{1 - x^2} + (1 - p)\sqrt{1 + x^2}]}{\sinh^{-1}(x)} f_p(x), \end{aligned} \quad (3.8)$$

where $f_p(x)$ is defined as in Lemma 2.2.

Therefore, $\frac{1}{3}G(a, b) + \frac{2}{3}Q(a, b) < M(a, b) < \lambda_0 G(a, b) + (1 - \lambda_0)Q(a, b)$ for all $a, b > 0$ with $a \neq b$ follows from (3.8) and Lemma 2.2. This in conjunction with the following statement gives the asserted result.

- If $p < 1/3$, then equations (3.5) and (3.6) imply that there exists $0 < \delta_1 < 1$ such that $M(a, b) < pG(a, b) + (1 - p)Q(a, b)$ for all $a, b > 0$ with $(a - b)/(a + b) \in (0, \delta_1)$.

- If $p > \lambda_0$, then equations (3.5) and (3.7) imply that there exists $0 < \delta_2 < 1$ such that $M(a, b) > pG(a, b) + (1-p)Q(a, b)$ for all $a, b > 0$ with $(a-b)/(a+b) \in (1-\delta_2, 1)$.

□

Proof of Theorem 1.3. We will follow, to some extent, lines in the proof of Theorem 3.1. First we rearrange terms of (1.3) to obtain

$$\beta_3 < \frac{C(a, b) - M(a, b)}{C(a, b) - H(a, b)} < \alpha_3.$$

Use of $C(a, b)/A(a, b) = 1 + x^2$ followed by a substitution $x = \sinh(t)$ gives

$$\beta_3 < \phi(t) < \alpha_3 \quad (3.9)$$

where

$$\phi(t) = \frac{t[\cosh(2t) + 1] - 2\sinh(t)}{2t[\cosh(2t) - 1]}, \quad |t| < \log(1 + \sqrt{2}). \quad (3.10)$$

Since the function $\phi(t)$ is an even function, it suffices to investigate its behavior on the interval $(0, \log(1 + \sqrt{2}))$.

Using power series of $\sinh(t)$ and $\cosh(t)$, then (3.10) can be rewritten as

$$\phi(t) = \frac{\sum_{n=1}^{\infty} [2^{2n}/(2n)! - 2/(2n+1)!] t^{2n+1}}{\sum_{n=1}^{\infty} [2^{2n+1}/(2n)!] t^{2n+1}}. \quad (3.11)$$

Let $c_n = 2^{2n}/(2n)! - 2/(2n+1)!$ and $d_n = 2^{2n+1}/(2n)!$. Then

$$\frac{c_n}{d_n} = \frac{1}{2} - \frac{1}{(2n+1)2^{2n}}. \quad (3.12)$$

It follows from (3.12) that the sequence $\{c_n/d_n\}$ is strictly increasing for $n \geq 1$.

Equations (3.11) and (3.12) together with Lemma 2.1 and the monotonicity of $\{c_n/d_n\}$ lead to the conclusion that $\phi(t)$ is strictly increasing in $(0, \log(1 + \sqrt{2}))$. Moreover,

$$\lim_{t \rightarrow 0^+} \phi(t) = \frac{c_1}{d_1} = \frac{5}{12}, \quad \lim_{t \rightarrow \log(1+\sqrt{2})} \phi(t) = 1 - \frac{1}{2 \log(1 + \sqrt{2})}. \quad (3.13)$$

Making use of (3.13) and (3.9) together with the monotonicity of $\phi(t)$ gives the asserted result.

□

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